Continuum-Based Numerical Simulation of Static and High-Strain Dynamic Pile Load Testing Adopting Advanced Soil Models

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Certificate of Original Authorship

I, **Mehdi Aghayarzadeh**, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This Research is supported by the Australian Geovernment Research Training Program.

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List of Research Papers

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Peer Reviewed Conference Papers:

- Aghayarzadeh, M., Khabbaz, H., 2019, 'Numerical Simulation of Concrete Pile Groups' Response Bored in Cemented Sand Deposit under Axial Static Load Testing', **7th International Symposium on Deformation Characteristics of Geomaterials**, Glasgow, UK.
- Aghayarzadeh, M., Khabbaz, H., Fatahi, B. 2018, 'Evaluation of Bored Piles Behaviour in Saturated Loose and Dense Sand during the Static Load Testing', paper presented at the **5th GeoChina International Conference**, Hangzhou, China, pp 75-89. *
- Aghayarzadeh, M., Khabbaz, H., Fatahi, B. 2018, 'Numerical Analysis of Concrete Piles Driving in Saturated Dense and Loose Sand Deposits', **9th European Conference on Numerical Methods in Geotechnical Engineering**, Porto, Portugal, pp 1031-1038.
- Aghayarzadeh, M., Khabbaz, H., Fatahi, B. 2018, 'Evaluation of Reaction Piles Effect on Test Piles in Static Load Testing Using 3-D Numerical Analysis', **10th International Conference on Stress Wave Theory and Testing Methods for Deep Foundations**, San Diego, USA, pp 68-80.
- Aghayarzadeh, M., Khabbaz, H. & Fatahi, B. & Terzaghi, S. 2017, 'Continuum Numerical Modelling of Dynamic Load Test for Steel Pipe Piles', **International Conference on Advancement of Pile Technology and Pile Case Histories**, Bali, Indonesia, pp (F4) 4-9.

* The paper presented in 5th Geo-China International Conference was nominated as a selected and high quality paper for consideration in International Journal of Geomechanics (ASCE).

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NOTATIONS

Latin Letters

A	Cross section of pile
c	Wave propagation speed
c	Soil cohesion
D	Pile diameter
D_r	Relative density
e_{c0}	Critical void ratio at zero pressure
e_{d0}	Minimum void ratio at zero pressure
e_{i0}	Maximum void ratio at zero pressure
E	Elastic modulus
E_{50}	Secant elastic modulus for a mobilization of 50% of the maximum shear strength
E_{50}^{ref}	Secant stiffness in standard drained triaxial test
E_M	Menard modulus
E_{oed}^{ref}	Tangent stiffness for primary oedometer loading
E_{ur}^{ref}	Unloading / reloading stiffness
F	Force measured at the gauge location
F_c	Correction factor
$F_m(t^*)$	Measured force at any time at the gauge location
$F_T(t)$	Force measured at the pile head
h_s	Granular hardness
J	Damping factor

J_c	CASE damping factor
k_0^{nc}	k_0 for normal consolidation
L	Length of pile
L_c	Length of stress wave
M	The total mass of a pile
m	Power for stress level dependency of stiffness
m	Maximum steps
m_R	Stiffness increase for a 180 degree reversal
m_T	Stiffness increase for a 90 degree change of strain path direction
n	Sensitivity of granular skeleton to change of pressure
n	Number of sub-steps
P_s	The mean particle pressure
P^{ref}	Reference stress for stiffness
Q_{ave}	Average individual pile head load
q	Soil quake
R	Radius of elastic range
R_d	Dynamic soil resistance
R_{int}	Interface strength reduction factor
R_f	Failure ratio
R_s	Group settlement ratio
R_s	Static soil resistance
R_{toe}	Static toe resistance

S	Settlement without the influence of reaction piles
S_m	Settlement considering the influence of reaction piles
t_{max}	The time of impact
t^*	Time corresponding to measured force and velocity (any time)
t_1	Impact time (time corresponding to first peak in force and velocity traces)
t_2	Time corresponding to wave reflection from pile toe
v	Velocity measured at the gauge location
v_b	Velocity of the pile toe
$v_m(t^*)$	Measured velocity at the gauge location
$v_R(t)$	The particle velocities of the generated waves due to the resistance
$v_T(t)$	Velocity at the pile head
$v_T^d(t)$	Pile top velocity due to the downward travelling wave caused by soil resistance
$v_T^u(t)$	Pile top velocity due to the upward travelling wave caused by soil resistance
W_D	Downward travelling wave
W_U	Upward travelling wave
Z	Pile impedance

Greek Letters

α	Exponent describes the transition between peak and critical stress
α	Influence of mass in the damping
β	Exponent represents the change of stiffness at current density
β	Influence of stiffness in the damping
β_R	Material constant
$\gamma_{0.7}$	Threshold shear strain
Δt	Duration of dynamic loading
δt	Time step used in dynamic calculations
σ_c	Compressive stress
σ_T	Tensile stress
υ_{ur}	Poisson ratio for unloading-reloading
ϕ_c	Critical state friction angle
χ	Material constant represents stiffness degradation

Acronyms

BOR	Beginning of restrike
CAPWAP	CAse Pile Wave Analyses Program
CL	Centre line
CSX	Maximum compressive stress

DSX	Maximum displacement of pile
EMX	Maximum transferred energy at gauge location
EOD	End of driving
HP	Hypoplastic
HS	Hardening Soil
HS-Small	Hardening Soil with Small Strain Stiffness
IGS	Intergranular Strain
LE	Linear elastic
MC	Mohr-Coulomb
PDA	Pile driving analyser
PPV	Peak particle velocity
RMX	Maximum static soil resistance
RTL	Maximum total resistance
RX0	Maximum static soil resistance with CASE damping factor zero
SDMT	Seismic dilatometer test
SET	Permanent displacement of pile
SFR	Static shaft resistance

SFT	Total shaft resistance
TC	Temporary compression
WEAP	Wave equation analysis program

ABSTRACT

Piles are generally used to carry structural loads when the soil at the ground surface is low in strength or the loads are substantial. It is very common to conduct pile load testing to assess whether the piles will behave as predicted in the design stage. Static load testing (SLT) is considered to be the benchmark for assessing the performance of piles since it is known the most fundamental way of pile load testing. However, this kind of test is time consuming and expensive, and in cases such as offshore operations, SLT is generally not possible for many cases. In spite of this, powerful computer programs for pile testing simulation have been revolutionised and are available. Of these different methods, the dynamic load testing (DLT) method for assessing the static bearing capacity of piles is of major interest and importance. A dynamic pile test is based on the signal matching technique in which the pile-soil system is modelled using the CAse Pile Wave Analyses Program (CAPWAP). This program tries to calculate the tip and side resistance of embedded piles and produces a force versus time signal which matches the measured data. The signal matching analysis uses a one-dimensional wave equation analysis of piles based on the Smith model to differentiate between toe and shaft resistance, to ascertain the distribution of frictional resistance along the pile shaft to determine the tensile and compressive stresses during pile driving. However, this technique uses a mass–spring–dashpot system to model the soil media surrounding and below the toe which imposes some restrictions such as being user-dependant process and using constant uncommon soil parameters such as quake along the pile length, regardless of soil strata, which can be layered or uniform. Furthermore, using CAPWAP to analyse pile driving interrupts the continuity of different stages of pile modelling from simulating pile driving, quality control, and investigating settlement. GRLWEAP or CAPWAP generally should be used

with a second software package such as PLAXIS in order to investigate any subsequent settlement or interaction.

In order to overcome the aforementioned limitations and assess pile behaviour during load testing in more detail, so-called continuum numerical models using the finite element program PLAXIS are established. In these numerical models, wave propagation, the static and dynamic response of piles during load testing for solid concrete piles and open-ended tubular steel piles are evaluated. In fact, the numerical simulations in this study are a remarkable improvement compared to the previous numerical studies because when simulating pile load testing, different soil models such as the Mohr-Coulomb, hardening soil, hardening soil with small strain stiffness and hypoplastic with intergranular strain are utilised to carry out a more rigorous deformation analysis.

To investigate the capability of the numerical model, the dynamic and static responses of a driven steel pipe pile monitored as part of a highway bridge construction project in New South Wales, Australia is simulated and numerically analysed using the finite element method. During these dynamic and static load testing simulations, a hardening soil model with small strain stiffness is used to obtain the best correlation between the large and small strains, while the pile is under a static load and being driven. The numerical predictions obtained using two-dimensional continuum finite element simulations are then compared with the corresponding predictions obtained from the CASE method and CAPWAP program to evaluate the predictions. Moreover, the total and static soil resistances as well as displacement and velocity traces obtained from numerical model are compared with the existing data acquired from the field measurements. The results indicate that the hardening soil model with small strain stiffness exhibits a reasonable correlation with the field measurements during static and dynamic loading.

Evaluation of static and dynamic pile load testing based on the continuum based finite element model has many advantages for geotechnical engineers dealing with pile design, because an established continuum numerical model can assess pile testing under more realistic conditions. This model can also be used to evaluate the performance of piles under different loading conditions on a single pile or group of piles, and piles built close to existing structures. Furthermore, this method retains the continuity of different stages of modelling from simulating pile driving, quality control, and investigating settlement, while all these analyses are carried out using one appropriate finite element based software.